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HUMAN FACTORS IN DESIGN OF PASSENGER SEATS FOR COMMERCIAL AIRCRAFT--A REVIEW

Technical Report
NASA Grant No. NGR 47-005-181

Submitted to:

National Aeronautics and Space Administration
Scientific and Technical Information Facility
P.O. Box 8757
Baltimore/Washington International Airport
Maryland 21240

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ABSTRACT

This paper presents the results and conclusions of much of the seat comfort and safety research since the early part of the century. The approach is a blend of the empirical and theoretical human factors and technical knowledge of seated humans under static and dynamic conditions experienced on commercial aircraft.

INTRODUCTION

The progress of civilization has made mankind more and more dependent on seats. However, seats can not be good servants of humanity unless they have been so constructed as to fulfill our biological and psychological needs. In the past, seats, almost without exception, have been constructed more for the eye than the back (1). Some fashionable design is desirable but it seems that seat comfort is much more related to the anatomical and physiological characteristics of the sitter. These characteristics are even more important for health reasons, when you consider, the total time a person spends in a seat daily. It's conceivable that, in the U. S., a person could spend 10 or more hours a day in seats--eating breakfast, going to and from work or school, working or listening to lectures, eating lunch and dinner, relaxing at home, and a variety of activities requiring a person to sit. Thus, the seat can affect the health of individuals over an extended period of time as well as their immediate comfort.

Most of a person's activities are performed in three basic body positions: standing (also walking and running), sitting, and reclining. For safe, healthy, and confortable performance in any of three positions, proper body support required; the muscular system is not capable of long-term efficient work without it (6) and fatigue or general discomfort at the very least will result.

Design of support systems for a sitting body position, i.e. seats, requires fundamental consideration of overall and regional human responses to both dynamic and static environemnts. Broadly, the most complex design problem occurs with transportation seating because there is a complex interlacing of long periods of static environmental conditions with random and mostly unpredictable changes in such environmental conditions as linear and angular accelerations and vibrations (6). Therefore, compsoite requirements for the static and dynamic conditions must be fused into a complex entity if safety, health, and comfort are to be properly attained (6).

BIO-STATIC CONSIDERATIONS FOR A SEATED PERSON

Anatomy and Physiology

The basic problem in seat design for man in a static environment is to accomodate him in a mechanical structure to eliminate localized pressure on the body. The solution requires a comprehensive understanding of the human skeleton and the suspension of body segments (6). Development of the Buttockscope, a device that gives a continuous dispaly of pressure patterns on any part of the body, has made such understanding easy without exposing human subjects to danger from overexposure to X-ray radiation (6).

The posture of a seated person is the most direct cause of discomfort while sitting because it is intimately associated with his anatomy and physiology and it is something over which he has some control. Generally, the skeletal, muscular, circulatory, and respiratory systems are directly involved and affected. The distribution of the weight of various parts of the body is important. Specifically, support should be provided for the abdomen (the pelvic bones, especially the ischial turberosities, and the underlying gluteal muscles): the back (the vertebrae, ribs, scapula, and the vertebral muscles); the bottoms of the feet; and the back of the head. The elbows and lower arms can also be supported comfortably. The longer the sitting period, the more important are back, head, and arm rests (see Figure 1). Footrests are required by smaller individuals to avoid pressure under the thighs.

A support fitting the lumbar concavity allows free movement at the thoraco-lumbar junction where the greatest amount of spinal movement occurs (8). The lumber erectores spinae muscles should be relaxed with full flexion of the trunk, enabling a relaxed position to be achieved without undue ligmentous strain. Support is probably most effective when provided within the range of the second to the fifth lumber vertebrae (8).

It is unlikely that there is one ideal sitting posture; several postures lie within an acceptable range because they are unlikely to

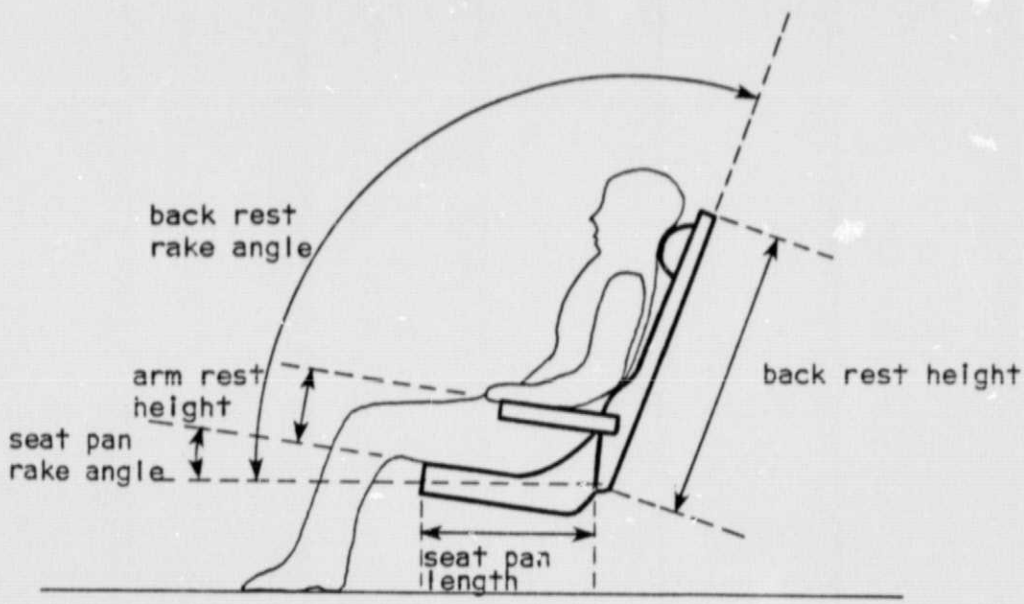

Figure 1. Typical Passenger-Seat Configuration

lead to disabilities and pain, even if maintained for a long time (8). Bad postures may be conveniently defined as those which are known to cause or to be associated with disabilities or pain or other abnormalities. It is likely that some people are more prone to acquire these abnormalities (8).

Sources of Physical Discomfort

The most restful position for sitting without adequate or any support for the back is to sit round-shouldered with the body hunched forwards in a slumped position (1). The spine is then bent forward to its utmost and is supported by its ligaments so that the back muscles can relax. Unfortunately, this postural position is a most unhealthy one. It causes undue pressure on the internal organs leading to poor breathing and other problems which may be respiratory, circulatory, or skeletal (1). For extended periods of sitting with this posture, serious conditions may result.

Seat design is unsatisfactory if it causes the sitter to assume and hold an unsatisfactory posture. The muscles employed may not work at their most efficient rate (15). The blood flow may not meet the requirements of a particular muscle group, so that insufficient O_2 is available for oxidation of carbohydrate in the muscles, or CO_2 (the product of oxidation) is not carried away sufficiently quickly (16). This local discomfort accumulates rapidly, even though the mechanical energy expended in the activity of sitting by the sitter is very slight. Further, pressure on nerves and blood vessels may lead to numbness, tingling (pins & needles), or anaesthesia (16).

Extensive experimentation with the Buttockscope has shown conclusively that the seated human body supports approximately 75% of its total weight on 4 sq. in. of the ischial tuberosities and the underlying flesh. A 200-lb man would therefore exert 37 psi on the tuberosities (6). Because compression load over a given unit body area is the factor which induces discomfort (fatigue), time under load determines the degree of compression fatigue to which a person is exposed.

Compression fatigue is the result of reduced blood circulation through the capillaries which affects the localized nerve endings. The person experiences sensations of ache, numbness, and pain (6). A person can delay the onset of compression fatigue by sitting erect with total body weight evenly distributed on both ischial tuberosities (6). The popular habit of shifting from one buttock to the other, or crossing the legs to relieve one buttock, does not reduce or delay compression fatigue but instead accelerates the rate of onset of fatigue. This is because greater pressure for each unit area is imposed on one buttock while the other is trying to restore blood circulation (6). Compression fatigue can be relieved if the body is allowed to recline at various angles aft of vertical (6). In this way more of the body area supports the weight (see Figure 1). The only recourse is for the person to stand for a while.

Finally, the body heat and sweat of the sitter needs channels for dissipation if he or she is to be comfortable and not overheated and wet. Spaces must be provided between the sitter's body parts and the areas of the seat in contact with them for circulation of air.

Psychological Discomfort

Every person has his own impressions as to what constitutes a comfortable "personal space". His concept of personal space depends on everything he perceives that makes an impression upon him, his social and psychological characteristics, his anxieties, and his attitude/belief systems. If he is seated, his concept also depends upon his personal anthropometric data (9). The designer of public seating systems can exercise control only over what a person will perceive and, to a greater extent, over the relationship between the personal anthropometric data and the characteristics of the seat. However, the actual system design may affect all of the above variables. Care must be exercised so that negative effects are not obtained as a result of a particular design. The seat may not be the most important variable affecting the sitter, but it is the one with which he has

the most intimate physical contact (5), and, as already mentioned, the one over which the designer exercises the most control.

A sense of safety and security is intimately associated with the feeling of comfort and vice versa (5). This feeling of comfort is a complex integrated response depending on all the previously mentioned physical and psychological variables. Physical discomfort can increase psychological discomfort and vice versa. An uncomfortable person might think that "time has slowed down" since he is made more conscious of minute elements of time by his discomfort. Social interactions causing embarrassment might cause him to feel too hot or restless as his blood rushes to the outer areas of his body. Offensive sensory perceptions such as loud noises, offensive odors, eye-sores, extremes in temperature, or compression fatigue may cause the sitter (as well as anybody else) to be irritable and impatient. Cleanliness, orderliness, and aesthetic quality are also important to the sitter. Hypertension is one result in sitters trapped into designs that are psychologically unsatisfactory. Micro-traumatizations must not be underestimated as agents injurious to health.

BIO-DYNAMIC CONSIDERATIONS FOR A SEATED PASSENGER ON COMMERCIAL AIRCRAFT

Physiological Effects

The primary goals of any high speed transportation system are safety and efficiency. After these, the physical comfort becomes of primary importance (11, 18). The basic comfort factors in a dynamic environment are seating, accelerations, noise and temperature (11, 18). Acceleration effects on the unrestrained human body depend in general upon their magnitude, duration and direction. They manifest themselves as stresses on the supporting structure of the body; they produce by way of various receptor organs a more or less pronounced reflex contraction of certain muscles; and they cause deformation and displacement of the soft organs of the body (6).

The body fluids, which circulate in preformed channels, will be displaced a minimal amount when the acceleration interval (the period of time over which the acceleration lasts) is less than 2 sec., but longer time intervals can result in considerable displacement and consequent loss of coordinated bodily and mental functions especially those functions requiring the vestibular organs (6). The latent response of the different body systems and their compensatory mechanisms are the primary considerations in determining human tolerance to acceleration forces. When the force period is within the latent response time, the compensatory mechanisms are not affected, and the whole body reacts as a viscous elastic system without sensing the true significance of the stresses (6).

Every time a vehicle accelerates in any of the six degrees of freedom of motion, the passenger's whole body is thrown slightly off balance. The passenger then expends energy, usually without thinking about it, in using his muscles to regain balance (16).

The dorsal cavity (head, neck, and spine) is a rigid spherical mass connected to movable shielded tube that extends the length of the torso. It responds to an abrupt force as a semi-rigid structural object (6). The magnitude of response is a function of the direction of the force. The brain is well protected within the structure through multiple flexible attachments (ligaments) and floats within a liquid that greatly increases natural protection. Assuming that the rigid structural process of skull and spine are not violated by crushing or puncture, the major threat to this segment is rapid movement of the spine to its angular limit. Such a movement in the neck area, immediately below the skull, has experimentally produced concussions by sudden stretching of the spinal cord (6).

The thoracic cavity (heart, lungs, and rib cage) is an entirely different structural and physiological system. Bony processes of the rib cage provide some natural protection to the internal organs, even though the ribs are felxible and move with breathing. Therefore, the ribs can be expected to carry a limited force, but unit loading must be small and spread over a large area. Fracture of the rib cage inward can cause damage to internal organs and may even puncture the heart or lungs (6). The heart can be displaced laterally the full width of the thoracic cavity by forces as low as 10g. Because the heart cannot be restrained directly, damage to this organ and the thoracic cavity is always a possibility (6).

The pelvic cavity (stomach, liver, intestinal system) contains no rigid structure and therefore functions as a true viscous/elastic system. It has the ability to extend to relativtly large distances in six directions and return to an original position without injury (6). All organs are soft and displace over one another in a fluid medium and are connected by flexible fibrous ligaments that will sustain injury if the differential displacement between organs exceeds ligament length (6).

The body extremities (arms, legs, hands, and feet) do not possess vital physiological functions. Their primary limitations are the spheres of movement which they cannot exceed without injury. Published

anthropometric data have completely defined these movements and angles for the reliable development of restraint mechanisms (6).

The effects of low amplitude vibrations on human physiology have been researched extensively. Bio-dynamic tests show that the predominant natural frequencies of the body depend not only on the direction of the vibratory excitation but also on the posture of the subject (4).

Vehicles transmit vibrations to their passengers. These vibrations are produced both by the power plant of the vehicle and by interaction of the vehicle with its supporting medium (17). Increases in speed of the vehicles often bring about increases in the vibration level that occupants of these vehicles must endure. Similarly, differences in the sizes of vehicles and their power plants produce changes in the frequency and amplitude of vibration, both of which are important factors in the effects of vibration on humans (17). Vibration in commercial aircraft is related to the problem of clear air turbulence and engine vibrations.

There are three ways in which humans can be exposed to vibration: (a) through a vibrating medium such as air or water, in which the human body is immersed; (b) particular body parts, such as the hands or feet, may be vibrated through direct contact with armrests, footrests or any other vibrating mechanical device supporting or contacting a person in some way; (c) vibration may be transmitted to the body as a whole through the torso as a result of direct contact with a vibrating structure (17).

Any physical structure, when excited by vibration, will amplify the input motion at certain frequencies and attenuate (damp) it at others (17). The human body being a very complex structure, exhibits different resonances for different body parts (17). At a frequency of 0-1 Hz, the head vibrates at somewhere near the amplitude of the seat. As frequency increases, the amplitude of head vibration increases and reaches a peak amplitude somewhere between 3-6 Hz. At this frequency

the head vibrates at an amplitude equal to 150-300% of the seat amplitude. The amplitude of vibrations transmitted to the head decreases progressively at higher frequencies. At 70 Hz, only about 10% of the amplitude of seat vibration may be expected to be transmitted to the head, (17) i.e. about 90% is damped.

Minimum tolerance to vertical vibration is in the region of 4-8 Hz and is attributed to resonance in the thoraco-abdominal system (4).

At lower frequencies the body tends to behave as a pure mass, i.e. moving as a rigid structure without remarkable relative displacements between its component parts (4). At higher frequencies, the transmission of vibration through the body becomes small, they body structures with low natural frequency tending to act as vibration isolators (4).

Under horizontal motion in either longitudinal (fore-aft) or transverse directions (side to side), an unrestrained body will exhibit a major resonance in the region of 1.5 Hz which can be suppressed by restricting the associated body movements. In such circumstances the predominant resonance will occur in the neighborhood of 5 Hz (4). In the region of higher frequencies, a relaxed posture reduces the transmission of vibration through the body thereby increasing the tolerable level and a similar effect is caused by the presence of cushioning on the surface of the seat (4). It is common for seats to possess a low frequency resonance (19).

It is believed that the body restraints (arm, back, and footrests) have a substantial influence on the response of the body to horizontal vibration and the seat shape could also affect the vertical resonances (4).

Psychological Effects

The static psychological factors apply to the dynamic situation as well, except that a sense of safety and security is probably more critical to the sitter in the dynamic case. Vibrations, accelerations and other factors of the sitter's physical environment which interact with his biological system might effect psychological disturbances. Feelings of distress or anxiety or even anger may result. The seat,

being more or less the interface between the sitter and his physical environment, has direct effects on the sitter's satisfaction with the ride. In the dynamic environment of a commercial aircraft, the sitter is concerned about crashes, turbulence, his stomach, whether or not he got to sit next to the window, the weather, his job, home, family, friends, etc. A comfortable seat might help relax him and ease any worries.

PASSENGER SEAT DESIGN AND TECHNOLOGY FOR COMMERCIAL AIRCRAFT

Based upon the foregoing human factors discussion, it should be possible to economically design seats for commercial airlines--seats that satisfy, say, the middle 90% of the U.S. population--given the necessary anthropometric data.

General Considerations

In order to design commercial aircraft passenger seats that satisfy, the user's biological and psychological requirements, certain characteristics of the expected users should be obtained. These characteristics include anthropometric and demographic data. Geographical characteristics of the surfaces over which the aircraft will fly will also be useful (11). Important, but more related to the design of the entire aircraft passenger cabin, are expected patterns of actions or activities of passengers when entering, riding in, and getting out of the aircraft (11). In the case of commercial aircraft passengers, the expected activities are reading, writing, eating, talking, and looking out of the window (18).

It is important to realize that the passenger seat should not be designed for the "average" person. Rather, a design should satisfy persons who fall at the extreme ends of the distributions of biological variables such as body size, physical abilities, and tolerances for discomfort. Many of the variables were described in the previous sections of this paper. Data of body dimensions and angles are presented later.

Another point of which to be aware is that the longer the distances involved on an operator's service, the more important all the preceding and following seat-design considerations become. It is encouraging to note the possibility of designing a seat that tends to channel the sitter gradually into better postures in the course of long journeys (more than one hour) (3).

To begin, a passenger seat is considered to have four main parts (5):

a. supporting structure

b. adjusting mechanisms

c. upholstery

d. fittings & accessories

The supporting structure involves safety, anthropometric and physiological considerations. The adjusting mechanisms and upholstery are concerned mainly with the sitter's physiological requirements; and fittings and accessories such as safety belts; foot, head, and arm wrests; and seat coverings are needed to satisfy the passenger's long-journey physiological requirements and to help insure a safe trip. These four parts will be described separately and interactively to some detail.

Supporting Structure

Two factors of the supporting structure will be described: strength and size. The design and construction of the seat must comply fully with the current Air Registration Board's regulations pertaining to strength (5). The seat must withstand a forward force of 9.0 g's, a downward force of 7.1 g's, an upward force of 4.1 g's, and a side force of 3.0 g's (12).

Maximum seat-passenger deceleration in response to aircraft deceleration is found to depend on the natural frequency of the seat containing the passenger, considered as a mass-spring system (15). The three principal qualities of a seat that relate to its ability to hold a passenger through a deceleration are the natural frequency of the seat, its static strength, and its ability to absorb energy in deformation beyond the elastic limit. The basic design problem is to determine a set of magnitudes for these qualities that will produce a seat that will serve for a deceleration of a given description. Presumably, this deceleration is the design requirement for the seat (15). (The design requirements for ability to hold a passenger are the decelerations of aircraft impact given in the previous paragraph).

Damping action in the seat-passenger system arises from friction between seat structural elements that bear on each other and more when the seat distorts under load; from high friction force between the passenger and the seat as he slides within the limits applied by the safety belt; and from the flexure of the passenger over his saftey belt (15).

Both damping and ability to hold a passenger through large decelerations refer to seat attachment to the aircraft passenger cabin floor and/or wall as well as the supporting structure itself, i.e., the seat frame. Although the above discussion has referred to the seat-passenger system with the seat as a finished product, the design problems of damping and strength for this system can easily be translated into ones for the supporting structure--attachment system by itself.

The direction of the seat is of prime importance in the supporting structure design. The directions considered are forward-and rearward-facing seats. Side-facing seats are unthinkable on commercial aircraft from a safety and comfort point of view. The proponents of forward seating point to the higher crash loads a seat of this configuration will sustain compared with a rearward-facing seat of the same weight (14). The proponents of rearward seating point to the greater protection from crash injury such seats provide when the seat does not collapse in a crash (14). A criterion for determining when the advantage of one type of seating should be traded for the other has been proposed. It is based on a measure of the relative maximum crash loads forward and rearward seats of the same weight will sustain; the anticipated relationship between the duration and magnitude of the peak crash deceleration likely in a modern aircraft; and an appraisal of the injuries that may occur to passengers in forward-and rearward-facing seats during such crash decelerations (14). Three points get further discussion: First, a smaller load per unit area is imposed on the rearward-facing passenger who is supporting his deceleration force with the broad area of his back. Thus, rearward seating avoids the flexing of the torso over the seat belt with the attendant danger of head injuries present in forward seating (14). Second, the force on the seat floor attachments and seat legs are smaller if the decelerating passenger is held at his hips by a seat belt in a forward-facing seat than it would be in a rearward-facing seat. This is because the rearward-facing seat has higher bending moments in the legs and floor attachments (14). Finally, the rearward-facing seats expose the

passenger to the shower of loose objects that fly to the front of the aircraft when a crash occurs (14).

In view of these difficulties it appears that the forward-versus rearward-seating controversy will be finally resolved only after carefully engineered seats of both types having equal weight have been evaluated under controlled conditions approximating aircraft crash decelerations (14). The relative quality of the seats could be judged on the two cardinal points:

1. Which one can withstand the more severe deceleration without collapse? (14)

2. For decelerations that do not collapse the seat, which seat holds the passenger through the crash deceleration with the least injury ? (14)

It is not necessary to distinguish between forward-and rearward-facing seats for the rest of the seat design considerations except in a few specific areas.

Materials with which to manufacture the supporting structure should be light weight, rigid, and have high strength to be economically efficient and meet the previously stated strength requirements. Steel, aluminum, fiberglass, and wood are rigid and have high strength. All have relatively low weights except steel but none have significant damping qualities except wood. However, wood has the important disadvantages of wearing down, splintering, and flamability (6).

The supporting structure (in conjunction with the cushions and upholstery) should be of such a shape and size to allow the passenger frequent changes of position (11) to various new positions in the seat, but it should also provide enough lateral support to help the passenger feel secure and comfortable during angular and lateral accelerations. Thus, individual seats are more desirable than bench types. The angles between the trunk and thigh and the thigh and lower leg were said to be important physiological factors of comfort in the first section of this paper. The unified dimensions and angles of the frame and cushions

must account for these factors. It should be noted that the (load) in-use contour, rather than the passenger-free contour, is more important for the angle and dimension considerations. More is said about dimensions, angles, and cushions later.

Adjusting Mechanisms

As previously mentioned, the "average" person with respect to all of the anatomical dimensions does not exist. Thus, seat adjustments are necessary to obtain comfort for passengers at the extreme ends of the distribution of anatomical dimensions (16). From a comfort standpoint, it would be desirable for a passenger to have the ability to adjust every angle and dimension somewhat to suit his or her own body. However, this concept is economically quite prohibitive and it is also really not necessary even for long journeys. In fact, most commercial aircraft passenger seats, including first class seats, have adjustable backrests only. Other possibilities are adjustable head rests, foot rests, and leg room.

The whole length of the spine can be made to share some of the passenger's weight if the seat back can be tilted back (16). The more it is tilted back, the more weight will the spine share until the passenger is in the reclining position. The ability to recline horizontally is not economically feasible on most commercial aircraft especially for short journeys. The range of backrest adjustment should be determined by a number of factors such as seat spacing within the aircraft passenger cabin, average flight time, and the passenger's physiological need to reduce and delay compression fatigue. It is evident that the angle of back rest adjustment had an important determining influence on the seat spacing, and upon seat positioning relative to aircraft structural bulkheads (5). To preserve adequate passenger space allowance without serious increase in pitch, extra angular adjustment may best be obtained in conjunction with a forward movement of the seat pan. The adjusting mechanism of this type of seat, incorporating an interconnecting linkage between the moving parts,

will necessarily be more complicated than that of the usual type of seat. The mechanism is usually in the form of a linkage used in conjunction with a coiled spring, or rubber bungy counterbalance arrangement to offset the passenger's weight. A lever extension of the linkage provides the passenger with a means of operating the mechanism (5). Other designs could depend merely upon the reaction of the passenger's feet on the cabin floor as a means of adjusting the sitting attitude. The method chosen should be simple, as light as possible, and positive in action. No undue effort by the passenger should be involved, i.e. the actuating control should be easily operated, and be mounted unobtrusively yet within easy reach of the average sized passenger when in the seat (5). A refined actuating control used in conjunction with electric, pneumatic or hydraulic power supply, may be provided. This will reduce the effort on the part of the passenger to merely pressing a push button, or the turning of a knob, but the disadvantages from an installational and maintenance point of view are self-evident (5). Also, the probability of failure of such an arrangement will be greater than that of the simpler mechanical lever system. The noise associated with electrical drive mechanisms should be kept within reasonable limits (5).

All adjusting mechanisms should be designed with the same deceleration requirements as the supporting structure (seat attachment and frame). Of course, all loads on the mechanisms must be considered additionally.

Upholstery

A very important factor in the design of comfortable passenger seating is the contour of back seat and seat pan. It should be emphasized that the free contour is of relatively little importance. The factor of major importance is the actual contour of the seat when it is occupied by the passenger.

The problem of establishing proper contour is made extremely difficult by the fact that, unlike the manufacturer of clothing who can offer a wide variety of sizes of his product to suit varying

individual builds and statures, the seat design engineer has the task of producing a seat that will fit satisfactorily and adjust itself to many different sizes, shapes, and weights of passengers (13). The seat must suit not alone the average height and weight, but must also be reasonably satisfactory to passengers of both extremes of stature and weight (13). It is as yet impracticable, because of cost considerations, to provide adjustments for seat height, depth, or contours to suit individual requirements. In short, the engineer has the rather complicated problem of pleasing the public with a single seat pan and back rest specification (13).

One method of reducing the problem of compression fatigue is to contour the seat so that it completely supports the passenger's entire body (6). Because most structural materials can be formed, they aid in closing the gap between passenger and seat. However, failure to achieve good contouring between passenger and seat results in compression fatigue (6). It seems that the engineer can't win! Since it is necessary to allow the passenger to periodically shift his position, it is better not to shape the seat pan and back rest to fully conform with the shape of the passenger's body, except that conformity which is necessary to give security and lateral stability. A concave back rest of varying curvature, according to which part of the passenger's back will be resting against it, will provide enough support to accomplish this (5). Support for the second to fifth lumbar vertebrae was said earlier to be especially important for comfort.

A certain amount of free movement in the back rest cushion, permitting it to move slightly vertically with the passenger as he floats on the cushion, is desirable. Limiting this movement, thereby obtaining damping of the passenger with respect to the seat pan is quite essential for comfort. Some damping is also achieved by cushion spring and padding (13). Research has indicated the desirability of maintaining a high damping value (per cent amplitude loss per cycle) and a low rebound ratio (ratio of the amplitude of a crest to the amplitude of the preceding adjacent trough) (13). The damping value is more important to

the reduction of passenger fatigue than surface softness. Thus, a comfortable seat does not mean a very soft or sloppy seat. Too much penetration of the passenger's body through the cushions, especially the seat pan cushion, transfers weight to tissues which were never intended to withstand it, and discomfort very quickly results.

The part of the seat pan supporting the ischial tuberosities should be flat and disposed horizontally so as to distribute body weight evenly over the tuberosities and retard the onset of compression fatigue (8). The chief advantage of unshaped seat pans is that there is less risk of localization of pressure on tissues ill-adapted to withstand it; the only advantage of the contoured seat pan is that it may use more of the ischial area for support. But variations in the size and shape of this area from individual to individual are considerable, so that any such shaping is of dubious value. It is better for the seat pan to be substantially plane (8). Scoop seat pan designs should be avoided.

Research on sitting posture has shown that there are many postures in which there is slack. This can reduce markedly the deceleration tolerance of the seat (14). There are two types of slack: air and cushion. The passenger is supported away from the substantial structure of the seat back rest by a layer of cushioning.

The design of seats for all body positions requires a basic understanding of the materials available to accomplish the design objectives, both mechanically and physiologically (6). High-strength rigid materials are satisfactory for structural requirements, but they are unsatisfactory for human habitability or the relief of fatigue. The soft pliable materials which reduce fatigue are not capable of resisting high-stress conditions. Optimum design of a seat is, therefore, dependent upon proper interaction of pliable and rigid materials to meet the seemingly incompatible requirements of man and his environment (6). A review of seat materials is given in Table 1.

The usual approach to seat upholstery design has been to employ a foam rubber seat-cushion, in which the rubber itself serves as both

Material	Physiological Requirements							Mechanical Requirements				
	Soft	Pliable	Stretchable	Porous	Damping	Formed	Rigid	High Strength	Formed	Weight Low	High	Damping
Steel						x	x	x	x		x	
Aluminum						x	x	x	x	x		
Fiberglass						x	x	x	x	x		
Wood					x	x	x	x	x	x		x
Wire Mesh		x		x	x	x	x	x	x	x		x
Nylon Net	x	x	x	x		x		x	x	x		
Sand	x	x		x	x	x	x	x	x		x	x
Liquids	x	x			x	x			x		x	x
Inflatable Structures	x	x			x	x	x	x	x	x		x
Rubber Foam	x	x	x	x		x			x	x		
Fabrics	x	x	x	x			x	x		x		
Plastic Spheres	x	x			x	x	x		x	x		x

Table I. Material Requirements for Seat Design (6).

spring and cushion. In this foam rubber construction air cells provide a certain degree of air damping.

Flat and zigzag assemblies have the advantages of low cost, light weight, limited rebound tendency (low rebound ratio), and substantial space savings when used in the back rest permitting a substantial gain in knee room for the passengers (13).

In addition to the advantages previously mentioned for spring assemblies, these should also have minimum metal-to-metal contacts and provide lateral stability and damping in conjunction with cushions (13).

The degree of resilience of seat upholstery is of considerable importance for comfort (5). The seat pan and back rest cushion surfaces should to some extent conform to the shape of the passenger in order to minimize pressure points; on the other hand, the degree of resilience should not approach that of pneumatic upholstery, nor should the cushions have the characteristics of the hammock-type seat for Alternative form of upholstery equally suitable for seat pans, back rests, and arm rests, may be provided by cushions of expanded rubber or light density fibrous materials. The thickness of the cushion to give the desired resilience will depend upon the nature of the material used as a filling; bottoming is not permissible under any accelerations which are likely to be met, especially in normal flight (5). Examples of fibrous materials which are used for this purpose are felt, rubberized hair, cotton, kapok, and superfine fiberglass. Considerable weight saving is effected by the use of fiberglass (5). It is important that whatever material is used, surface ventilation of the cushions must be maintained, particularly if the seats are to be used in aircraft operating under tropical conditions, nor should any appreciable change in resilience occur due to climatic variations (5). In each instance, the selected material should if necessary, be treated so that it possesses the following properties (5):

(a) resistance to flame

(b) resistance to vermin and bacteria

(c) low moisture absorption.

In order to prevent the cushions from working down into the spring assembly with resultant breakdown and wrinkling, protecting pads are used (13). These pads have an influence on the impression of surface softness, which is due to a change in pressure distribution between the cushion and passenger when a protecting pad is used. The pads also have a minor damping effect. Their use is justified principally by the greater freedom from sagging and wrinkles which they provide (13).

Fittings and Accessories

Head rests are a comfort necessity, especially for long flights. Adjustable ones are recommended. Control of an adjustable head rest should be easy for the normally-seated passenger (5). A soft pillow should be provided to suit the varying head and shoulder configurations of the passengers. The adjustment of the pillow in the plane of the back rest will be integral with that of the head rest (5). Where the head rest is basically an extension of the back rest, it is necessary to make the pillow separately adjustable. This can be simply achieved by attaching the pillow to twin straps passing over each side of the back rest upholstery. In all cases the pillow should be easily removable to cater to the passenger who does not wish to use it, and for periodic cleaning (5). For long flights (greater than one hour), the provision of ear flaps for lateral head support is recommended. The distance of the ear flaps from the seat pan must be variable in order to prevent fouling of the shoulders of tall passengers (5). Since the required adjustment of both the head rest and the ear flaps is the same, it is suggested that the two items can be made integral. The ear flaps should be large enough to prevent the head of the sleeping passenger from rolling off the head rest. Where ear flaps are not used, a slight concavity in the head rest surface will assist in stabilizing the head; the provision of a shaped pillow will also be beneficial in this respect (5). Where flight times are short, head rests are merely an encumbrance, interfering with vision and making an interior appear crowded.

A foot rest should be provided to accomodate passengers at the short ends of the distributions of lengths of the thigh and lower leg. The foot rest relieves the pressure of the seat pan against the areas of the passenger's body behind the knees and under the thighs. Foot rests also allow any passenger to help place himself in a comfortable position. The surface supporting the foot should be insulated as much as possible from aircraft vibration transmitted through the floor structure. Otherwise, the fatigue effect on the passenger may be serious (5). In the form of a ramp, a foot rest should have an adjustable angle of inclination relative to the floor of the aircraft, ranging between 0° and 30° (5). The foot rest should avoid any tendency of the passenger's heels to slip down the ramp and prevent excessive flexing of the passenger's feet (5).

Arm rests help the passenger solve the problem of what to do with his hands and arms and help delay fatigue in the arms of the passenger who is reading a book or magazine. They should be as soft as possible to reduce pressure on the elbows, yet strong enough to give the arms support when the passenger uses them for reading and when he uses them to assist a shift in position or even standing up from the seat. Arm rests should be relatively low and can be adjustable to suit a widely varying population.

A very important factor in the overall seat design for comfort is the style of upholstery covering and physical characteristics of the material used. Deep V or U channels are important to dissipate body heat and decrease body sweat. The material for upholstery coverings should possess the following characteristics (5):

(a) be lightweight

(b) be durable, with good abrasive resisting qualities

(c) have high tensile strength

(d) be resistant to dilute acids and alkalies

(e) be easily cleaned, and

(f) be obtainable in a variety of colors.

There exists a wide choice of materials with these properties. Broadly, these materials can be divided into two groups: leather or leather substitutes, and woven fabrics. The advantages in favour of leather or leather substitutes are that they can be very readily cleaned, and they have good wearing qualities (5). The chief disadvantages are that, under low temperature conditions, the surface feels too cold, and under very warm or humid conditions the surface feels too hot. The low surface friction of these materials, which are usually smooth-surfaced, may constitute a source of inconvenience to passengers and necessitate a steeper angle of rake than would be otherwise necessary in order to prevent the occupant from slipping off the seat. Furthermore, these non-porous materials have poor sound absorption coefficients, and do not assist noise reduction within the aircraft passenger cabin (5). Fabrics, although possessing greater decorative characteristics than leather materials, are not so easily cleaned. They do however, possess to some extent the other properties listed, and in addition are more pleasing to touch over a wide temperature range (5). These porous materials are of benefit in noise absorption. If a patterned fabric is chosen, the pattern should be small to facilitate matching or blending of junctions between adjacent shaped surfaces (5).

The route and area of flight operations has a large influence on the choice of color of the upholstery as part of the cabin color scheme (5). For example, in temperate climates warm colors (yellow, orange, red, reddish-violet, and in between shades) should predominate, whereas in tropical zones a cooler motif (blue, green, blue-violet, blue-green and greenish-yellow) is desirable. Where an aircraft operates over both zones during its journey, a "neutral" color should be chosen, and the warm or cold effects required at different stages can be provided by suitable cabin lighting (5).

Fabric seat coverings, being easily soiled, may be protected by the provision of sets of loose covers, especially for the head rest;

this will avoid frequent removal of the seat coverings (5). For simplification of laundering the loose covers, the use of securing tapes is suggested. The material chosen for loose covers should have non-fade qualities which should persist even after repeated washings. Provision should be made for easy attachment and removal of upholstery coverings to facilitate replacement, and disinfecting of the cushion or filling (5).

The elasticity of the upholstery covering is an important characteristic. When the material is taut, additional members of the spring assembly are brought into partial action as compared with the condition where the fabric is so elastic to permit the passenger to penetrate into the cushion surface and ride primarily only on the part of the spring assembly immediately below him (13). Thus minimum stretch and maximum elastic limit specifications must be considered (13).

Seat Dimensions and Angles

For the purpose of defining standard seat dimensions, it is convenient to think of the human body as being made up of five jointed parts (5):

(a) the head

(b) the trunk (chest and abdomen)

(c) the thigh

(d) the lower leg

(e) the foot

The upper and lower arm might also be included in this system for purposes of arm rest design. There are comfortable angular limits for each of the joints between these parts, and the design of a passenger seat must accomodate these limits if comfort of the passenger is to be assured. Relaxation in the reclined seated position normally necessitates an angle approaching 180 degrees between the head and the trunk. In this

position the neck is extended, and it has been found by experience that some measure of relief will be afforded to persons, susceptible to air sickness, who adopt this head attitude (5). Thus, the head rest should support the head at this angle, but in order to accomodate different passenger preferences, provision should be made to support the head in varying angular positions relative to the trunk. This is especially desirable for the passenger who wishes to take up the "alert" attitude, where the head naturally assumes a posture near the vertical (5).

If the angle between the trunk and the thigh is less than 90 degrees, the back muscles are strained and the abdomen is compressed. It is recommended that this angle should not be less than 100 degrees when the passenger is seated in the alert position. For flights of long duration, this angle should not be less than 125 degrees (5). The full range of movement of the knee joint, from the positions of full flexion to full extension, has been found to be 130 deg. The attitude adopted by the seated passenger depends upon the length of the lower leg, and the position of the foot rest relative to the seat; it also depends upon the height of the forward compressed edge of the seat pan above floor level, and on the angle of the pan relative to the horizontal(5). The active range of foot flexion has been found to be 45 deg., the limiting angles between the lower leg and the foot being 75 deg. and 120 deg. respectively. A carefully positioned foot rest permitting a rest angle between the limits stated will normally be required (5).

It is unlikely that discomfort can be avoided by simply matching each body dimension with the equivalent seat dimension, as if the interface were static. What seems to be critical is the relation of any one dimension with the others and with expected sitting behavior.

<u>Seat heights</u> should be low to suit short passengers since those with long legs will also find them comfortable if the seat isn't too low and there is enough leg room (8). The seat is too low if an acute angle between trunk and thigh occurs for the passenger with long legs (8). Also, lumbar concavity cannot be maintained when the seat is lowered beyond a certain limit (8).

It appears that there is some conflict between the need for a low seat, in order to accomodate as wide a range of the population as possible without under-thigh pressure, and the need to avoid excessive hip flexion and the lumbar convexity which may accompany it (8). More than a single seat height may be necessary to cover the range from the tallest male to the smallest female; ideally, the former requires a 19-in. seat height (99th percentile) and the latter a 15-in. seat height (99th percentile), even when wearing shoes (excluding women's high heeled shoes) (8).

Differences between the seat height and the length of the lower leg affect a person's use of the back rest. Generally (for 80-90% of sitters studied), anything in excess of 1/2 in. of seat height above the length of the lower leg discourages the sitter from using the back rest. Most sitters prefer the seat height to be the same as the length of the lower leg (12). There is no discomfort if the seat is as much as 2 in. too low. Thus a seat to be used by both sexes should not exceed 17 in. in height before a person sits on it. Even at 17 in., unless the depth of the seat pan is only 15 in., it is essential to provide a foot rest for almost 50% of the women, men of short stature, and young teenagers. A seat height of 16 or 16 1/2 in. is strongly recommended (12).

Any particular dimension selected for the seat pan length (measured from the compressed line of the back rest) is a compromise dimension. This is because the need of adequate leg support for long legged male passengers, and the avoidance of pressure and chafing behind the knees for short legged female passengers has to be given fair consideration (5). The seat pan length should be less than the length of the thigh for two reasons: (a) to allow the buttocks to sink into the back rest so that the lumbar vertebrae receive support; and (b) to avoid the possibility of irritating pressure on the calf of the leg (12). It is recommended that the seat pan length should not exceed 17 in., or perhaps 18 in. if a foot rest is provided (12).

The recommended dimensions and angles for many of the various

parts of the commercial aircraft passenger seat are summarized in Table 2.

Finally, two points of important practical concern are mentioned. The first point is the permissible weight of a seat consistent with economic operation of the aircraft. Because of the bulk and multiplicity of passenger seats, the aggregate weight constitutes a major portion of equipment weight on an aircraft (5). The second point to be considered in designing passenger seats is that the passenger accomodation layouts in the passenger cabin limit the seat dimensions and relative positions (5).

Dimension/ Angle	Cumberland & Bowey	Jackman	Dreyfuss	Hawkins
Seat pan height from cabin floor	12-14 in.	16.9 in.	16.5 in.	15.0 in.
Seat pan length	18.5 in.	20.0 in.	18 in.	17.0 in.
Seat pan width	19.0 in.	19.0 in.	23 in.	20.0 in.
Width between arm rest	18.0 in.	-	20 in.	-
Overall seat width	24.0 in.	-	27 in.	-
Height of back rest	25.0 in.	28.0 in.	31 in.	38.0 in.
Height of head rest				
-forward facing seat	8.0 in.	-		-
-backward facing seat	12.0 in.	-		-
Backrest width		19.0 in.	18.8 in.	22.0 in
Height of arm rests above pan	7.5 in.	8.5 in.	8.0 in.	8.0 in.
Seat pan rake angle (fixed)	5 deg $\leq$ angle $\leq$ 10 deg	-	4 deg.	7 deg.
Back rest rake angle (with respect to horiz.)				
-alert position	$\leq$ 110 deg.	-	(128 deg)	(115 deg)
-reclined position	$\leq$ 125 deg.	-		
Distance between seats (leg room)				

Table 2. Recommended Dimensions and Angles

CONCLUSION

Two guiding principles emerge:

(a) the seat should provide evenly distributed support over the whole length of body in contact with it (16).

(b) the seat dimensions should suit long and short, as well as medium passengers and all the joint angles of a seated person are above 90 deg. and not more than 120 deg. Angles outside this range produce fatigue rapidly, because they correspond to unnatural attitudes. for muscles which are supposed to be relaxed (16).

It is wrong to assume that an optimally-designed commercial aircraft passenger seat is necessarity expensive (12). It is also inadvisable to attach final importance to the comfort ratings of the passengers. For example, support for the spine in the lumbar region is essential, yet many passengers are unaware when it is not provided. An expert would look for it. Passengers are also unaware that a firm seat is better physiologically than a very soft seat (12).

REFERENCES

(1) Akerblom, B. Chairs and Sitting.

(2) Branton, P. "Behavior, Body Mechanics and Discomfort", Ergonomics, 1969, Vol. 12, No. 2, 316-327.

(3) Branton, P. and Grayson, G. "An Evaluation of Train Seats by Observation of Sitting Behavior", Ergonomics, 1967, Vol. 10 No. 1, 35-51.

(4) Bryce, W.D. National Gas Turbine Establishment, U.D.C. No. 534, 613.64, Report No. R. 286.

(5) Cumberland, C.H. and Bowey, G.S. "Passenger Seats for Aircraft", Design, Sept. 1950, 250-255.

(6) Dempsey, C.A. "Body Support/Restraint", Product Engineering April 16, 1962, 106-117.

(7) Dreyfuss, H. "Seats for People", Machine Design, Nov. 10, 1960, 152-157.

(8) Floyd, W.F. and Roberts, D.F. "Anatomical and Physiological Principles in Chair and Table Design", Ergonomics, 1-2, 1957-59, 1-16.

(9) Hawkins, N.M. Passenger Comfort Limitations on the Design of High Speed Transportation Systems, Department of Transport Technology, Loughborough University of Technology TT 7309, July 1973.

(10) Jackman, K.R. "Greater Comfort for the Airline Passenger", Aero Digest, November 1948, 42-46.

(11) McFarland, R.A. and Stoudt, H.W., Designing for Passenger Comfort in High Speed Transportation.

(12) Oxford, H.W., Factors in the Design of Seats Used in Public Transport.

(13) Paton, C.R., Pickard, E.C. and Hoehn, V.H., "Seat Cushions and the Ride Problem", SAE Journal (Transactions). Vol. 47, No. 1, July, 1940.

(14) Pinkel, I.I. A Proposed Criterion for the Selection of Forward and Rearward Facing Seats, NASA cc-E-323, N65-83244, 1959.

(15) Pinkel, I.I. and Rosenberg, E.G., <u>Seat Design for Crash Worthiness,</u> National Advisory Committee for Aeronautics, Report 1332, 1957.

(16) Roberts, D.F. "Passenger Comfort-Seating", Bus and Coach, June 1963, 214-218.

(17) Shoenberger, R.W. "Human Response to Wholebody Vibration", Perceptual and Motor Skills, 1972, Vol. 34, 127-160.

(18) Richards, L.G. and Jacobson, I.D., Quality Evaluation I. Questionnaire Studies of Airline Passenger Comfort, Eronomics, 1975, Vol. 18 No. 2, 129-150.

(19) Leatherwood, Jack D., Vibrations Transmitted to Human Subjects Through Passenger Seats and Considerations of Passenger Comfort, NASA TN D-7929, June 1975.